Executive Report

on

Basic Research on Self-Organized Quantum Dots
and
Their Potential in Solar Cells and Novel Devices Applications
(Phase IV)

Year 2006

by

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14. ABSTRACT

This is the research output from our AOARD-supported work on basic investigation of self-assembled quantum dots and their potential applications during 2006. The research project is the fourth year of AOARD-support following the previous ones in 2003 2004 and 2005. During the past year, 6 international journal publications on self-assembled quantum dots and and quantum dot molecules, heterostructure solar cells and quantum dot solar cells were published. There were technical papers on different growth techniques for different patterns of quantum dot molecules, e.g. bi-quantum dot molecules, long chain quantum dot molecules, quantum dot rings presented at 14th International Conference on Molecular Beam Epitaxy (MBE 2006), 32nd International Conference on Micro-and Nano- Engineering (MNE 2006), Electronic Material Conference (EMC 2006) and ECTI-CON 2006. 3 papers on quantum dot molecule solar cells and their potential applications at high concentrated sunlight were also presented at major international solar cell conferences, i.e. 4th World Conference on Photovoltaic Energy Conversion (WCPEC-4), 21st European PVSEC and at MRS (Material Research Society) Fall Meeting 2006. All our journal and technical papers (17 in total) acknowledge financial supports from AOARD and Thailand Research Fund (TRF). Research work on quantum dot molecules based on InAs and InP materials will be investigated and their applications for high efficiency solar cells will be presented in the upcoming 2nd IEEE-NEMs (Nano/Micro Engineered and Molecular Systems) in 2007. Challenge of 30 % up efficiency quantum dot molecular solar cells will be our target of our research in 2007 and 2008.

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Abstract

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Introduction

The zero-dimensional nature of quantum dots is of great interest for novel nanoelectronic devices. For example, its application in quantum dot laser results in lasers having record low threshold current, allowing the device to operate very efficiently. Single-electron transport in the form of quantum-dot transistor leads to extremely low power electronics with high-speed performance, much needed in today technology such as fibre communication and portable telecommunication sets.

Energy and environmental problems are also of critical importance to mankinds. The higher the energy consumption, the greater the amount of environmental damage, gives rise to the needs for new energy solutions. The research team at SDRL started activities on solar cells in 1975 when the first oil crisis occurred. The team has extensive experience in solar cell development, from crystalline silicon, thin-film amorphous silicon, GaAs/GaAlAs heterostructure, to the more recent quantum structures, i.e. quantum wells and quantum dots. Our research focuses on quantum dots for solar cell applications. The zero-dimensionality of quantum dots is the motivation for the research. InAs quantum dots have good response at long wavelengths of solar spectrum. Hence, an integration of quantum dots in solar cell structure will give higher efficiency of solar energy conversion. In addition, InP quantum dots are also another candidate for high efficiency quantum dot solar cells due to their wider bandgap which gives better response at visible region of solar spectrum. However, novel epitaxial growth of high density InP quantum dots with appropriate capping layers is needed to be explored.

Applications of quantum dots with the best commercial potential is in high-performance laser diodes providing 1.3 and 1.55-μm wavelengths for fibre communication systems. Quantum dots with appropriate dot size and uniformity are key to such devices, yet there are various aspects of controlling growth parameters of quantum dots in MBE process not fully understood.

Self-alignment of quantum dots by different modified growth techniques are investigated. This could lead to novel nanoelectronic devices such as single-electron devices and quantum dot set for quantum cellular automata.

Quantum rings and their structure transformation to bi-quantum dot molecules are also exciting research topic for spintronics and quantum information systems.

Research Outputs

In 2006, the research outputs are concentrated on self-assembled quantum dot molecules (QDMs) and their potential applications. The research outcomes were published and presented in international journals and conferences 17 in total (see attached reprints and documents). Self-assembled lateral InAs quantum dot molecules are grown using our original MBE growth technique of thin-capping-and-regrowth process. This unique quantum nanostrusture is reproducible and controllable via in-situ RHEED monitoring.

Self-assembled quantum dot molecules have higher dot density than as-grown quantum dots by one order of magnitude. Therefore, they have high potential to be applied in both lasers and solar cell structures. By repeating the thin-capping-and-regrowth MBE process for several cycles, high-density quantum dot molecules of more than 10^{12} cm^{-3} are obtained. This high-density quantum dot molecules with multi-stacked structure is used in solar cell devices. 24.5 % efficiency InAs quantum dot molecule solar cell was achieved in March 2006. The research result was presented at WCPEC-4, Hawaii in May 2006. This research outcome was confirmed by 25.9 % efficiency InAs quantum dot molecules solar cell and its stable performance at high concentrated sunlight (up to 4 suns). This research work was presented at 21st European PVSEC, Dresden in September 2006.

One drawback of InAs quantum dot molecule solar cell is its low open-circuit voltage (0.7 V) which is the bottle-neck in upgrading its efficiency. Wider bandgap nanostructure semiconductor is needed in the improvement. We are looking forward to studying InP quantum dots for new structure of quantum dot molecule solar cells having higher open-circuit voltage and better response at visible wavelength of solar spectrum. Higher dot density and appropriate capping material for InP quantum dot molecules are under investigation.

Quantum dot molecules with elongated nanostructure exhibit interesting polarization-dependent photoluminescence at room temperature. This is due to their anisotropic nature. Potential applications include polarized photo-emitters, needed in many optical communication systems. This work is published in Journal of Microelectronics Engineering, Vol. 83, pp. 1526-1529, February, 2006.

Control of dot number per QDM is possible by precise control of capping temperatures and thicknesses. At a low capping temperature of 430ºC, QDM with 4 satellite dots are realized and have a promising application for quantum dot cellular automata (QCA) which is a new approach for quantum computation having extremely low power

consumption. The same technique is also applied in gas-source MBE for the growth of quantum dot pairs (QDP) which are also useful for quantum computing based on the idea of quantum bit (qubit) using spintronics in a single quantum dot. This part of research work is the research-collaboration with Prof. Charles W. Tu of UC San Diego.

In 2007-2008, we will pursue the applications of multi-stacked high density quantum dot molecules, both InAs and InP, in solar cell heterostructure of GaAlAs/GaAs or AlInP/InGaP aiming at high efficiency solar cells. Meanwhile, research activity for basic study of single quantum dot, long chain quantum dots are also interesting for future quantum computing and nanoelectronic devices.

Summary

In 2006, 11 papers of our research work were presented at international conferences with 6 peer reviewed journal publications. Work on multi-stacked high-density quantum dot molecule solar cells was presented at major solar cell conferences. Research on high-efficiency quantum dot molecule solar cells and basic study of single quantum dot, quantum dot pairs and long chain quantum dots for future quantum computing and nanoelectronic devices will be conducted in 2007-2008.

List of Conference Papers (11 International)

1. "Improvement of PV Performance by Using Multi-Stacked High Density InAs Quantum Dot Molecules", Sirichai Ruangdet, Supachok Thainoi, Songphol Kanjanachuchai and Somsak Panyakeow, 4th WCPEC (32nd IEEE-PVSC), Hawaii, 7-12 May, 2006.
2. "Development of Cross-hatch Pattern on InGaAs/GaAs Virtual Substrate", Cho Cho Thet, Songphol Kanjanachuchai and Somsak Panyakeow, ECTI-CON 2006, Ubon Ratchathani University, May 10-13, 2006.
3. "The Effects of Rapid Thermal Annealing on Bi-Quantum Dot Molecules Grown by Gas-Source Molecular Beam Epitaxy", Suwaree Suraprapapich, Yaoming Shen, Yeshaiahu Fainman, Somsak Panyakeow and Charles Tu, Electronic Material Conference (EMC) 2006, Pennsylvania State University, Pennsylvania, U.S.A., 28-30 June, 2006.
4. "Spectral Response and Performance at Concentrated Sublight of Multi-Stacked High Density InAs Quantum Dot Molecule Solar Cells", Sirichai Ruangdet, Supachok Thainoi, Songphol Kanjanachuchai and Somsak Panyakeow, 21st European PVSEC, Dresden, 4-8 September, 2006.
5. "Evolution of Self-Assembled Lateral Quantum Dot Molecules", Suwaree Suraprapapich, Naparat Siripitakchai, Supachok Thainoi, Songphol Kanjanachuchai and Somsak Panyakeow, International Conference on Molecular Beam Epitaxy (MBE 2006), Tokyo, Japan, 3-8 September, 2006.
6. "Long Chains of Self-Assembled InAs Quantum Dot Molecules by Modified MBE Growth Technique", Sirichai Ruangdet, Nuttawut Budsayaplakorn, Supachok Thainoi, Songphol Kanjanachuchai and Somsak Panyakeow, International Conference on Molecular Beam Epitaxy (MBE 2006), Tokyo, Japan, 3-8 September, 2006.
7. "Self-Assembled Lateral Bi-Quantum-Dot Molecule Formation by Gas-Source Molecular Beam Epitaxy", S. Suraprapapich, Y.M. Shen, V.A. Odnoblyudov, Y. Fainman, S. Panyakeow and C.W. Tu, International Conference on Molecular Beam Epitaxy (MBE 2006), Tokyo, Japan, 3-8 September, 2006.
8. "Growth of Long-Range, Ordered InAs Quantum Dots on InGaAs/GaAs Cross-Hatch Virtual Substrate", S.omsak Panyakeow, Cho Cho Thet, Somchai Ratanathammaphan, Songphol Kanjanachuchai, 32nd International Conference on Micro- and Nano-Engineering 2006, (MNE 2006), Barcelona, 17-22 September, 2006.

9. “In-droplet-induced formation of InP nanostructures by solid-source molecular-beam epitaxy”, Wipakorn Jevasuwan, Somsak Panyakeow and Somchai Ratanathammaphan, 32nd International Conference on Micro- and Nano-Engineering 2006, (MNE 2006), Barcelona, 17-22 September, 2006.
10. “Self-Assembled Quantum Dot Molecules for Practical Nanostructure Devices: Bottom-Up Approach”, Suwaree Suraprapapich, Naparat Siripitakchai, Sirichai Ruangdet, Nuttawut Budsayaplakorn, Wipakorn Jevasuwan, Pornchai Changmuang, Supachok Thainoi, Songphol Kanjanachuchai, Somchai Ratanathammaphan, Montri Sawadsaringkarn and Somsak Panyakeow, submitted to 32nd International Conference on Micro- and Nano-Engineering 2006, (MNE 2006), Barcelona, 17-22 September, 2006.
11. “InAs/GaAs VS InP/GaAs Quantum Dot Molecules and their Potentials for Photovoltaic Applications”, Wipakorn Jevasuwan, Sirichai Ruangdet, Somchai Ratanathammaphan and Somsak Panyakeow, 2006 MRS (Material Research Society) Fall Meeting, Boston, 27 November-1 December, 2006.

List of Journal Publications (6 International)

1. “Regrowth of Self-Assembled InAs Quantum Dots on Nanohole and Stripe Templates”, Suwaree Suraprapapich, Songphol Kanjanachuchai, Supachok Thainoi, and Somsak Panyakeow, Journal of Microlithography, Microfabrication and Microsystems, Vol. 5, No. 1, pp. 011008-1 - 011008-5, January-March, 2006.
2. “Self-Assembled Lateral InAs Quantum Dot Molecules: Dot Ensemble Control and Polarization-Dependent Photoluminescence”, Suwaree Suraprapapich, Songphol Kanjanachuchai, Supachok Thainoi, and Somsak Panyakeow, Journal of Microelectronics Engineering, Vol. 83, pp. 1526-1529, February, 2006.
3. “Self-Assembled InAs Lateral Quantum Dot Molecules Growth on (001) GaAs by Thin-Capping-and-Regrowth MBE Technique”, Suwaree Suraprapapich, Songphol Kanjanachuchai, Supachok Thainoi, and Somsak Panyakeow, Journal of Solid State Phenomena, Vol. 121-123, 2006.

4. “Thin-Capping-and-Regrowth MBE Technique for Quantum Dots and Quantum Dot Molecules”, Suwaree Suraprapapich, Supachok Thainoi, Songphol Kanjanachuchai and Somsak Panyakeow, Journal of Vacuum Science and Technology B, Vol. 24, pp. 1665-1667, 2006.
5. “Quantum Dot Integration in Heterostructure Solar Cell”, Suwaree Suraprapapich, Supachok Thainoi, Songphol Kanjanachuchai, and Somsak Panyakeow, Journal of Solar Energy Materials and Solar Cells, Vol. 90, pp. 2968-2974, July, 2006.
6. “n-GaAlAs on p-GaAs Heterostructure Solar Cells Grown by Molecular Beam Epitaxy”, Supachok Thainoi, Suwaree Suraprapapich, Songphol Kanjanachuchai, and Somsak Panyakeow, Journal of Solar Energy Materials and Solar Cells, Vol. 90, pp. 2989-2994, July, 2006.

List of Conference Papers

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